# OPTICAL PROPERTIES OF A NOVEL GLASS CERAMIC RESTORATIVE MATERIAL

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## ABSTRACT

Robert Jackson Blackburn Jr: Optical Properties of a Novel Glass Ceramic Restorative Material
(Under the direction of Ryan Cook)

This study examined the optical properties of a dental restorative material manufactured from lithium aluminosilicate ceramic and reinforced with lithium disilicate. The property of translucency and the optical effects of various abutments on color were the primary focus of the study. Samples were prepared in thicknesses of 0.5, 1.0, 1.5, and 2.0 millimeters of both high (HT) and low (LT) translucency versions of the material. The samples were examined using standard photospectrometry practices. A baseline relationship between translucency and material thickness was examined and the effects of clinically relevant abutments on color change were studied. An exponential relationship between material thickness and translucency was observed but no significant difference in translucency of the HT and LT versions of the material was found. The change in color observed for the material was significant for both composite and titanium abutments, but not when zirconia was used as an abutment.

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| | |
|---|---|
| CR | Contrast Ratio |
| HT | High Translucency |
| LT | Low Translucency |
| mm | Millimeters |
| TP | Translucency Parameter |
| $\Delta E$ | Change in Color |

## CHAPTER I: INTRODUCTION

### Purpose of the Study

In order to be judged as a successful dental restoration, the material used must not only meet biological and mechanical requirements for longevity, but also meet demanding esthetic requirements to be satisfactory to the patient and provider. The interface between the esthetic characteristics and mechanical requirements offers a narrow window of overlap where restorative materials may exist that fulfills all expectations. Because patients are not typically able to assess the strength or fit of restorations, the esthetic component typically takes priority. In areas where the restorations are highly visible, this may be the only criteria by which success or failure is assessed by the patient.

The ability of the restoring dentist to create a naturally appearing restoration is dependent upon the optical properties of the restorative material. The material needs to not only possess qualities similar to natural teeth in translucency and color, but also be predictable in how the material will handle under different conditions. Value is typically a predictable factor for restorative materials, and the hue and chroma of a restorative material, while sometimes variable, can be modified with external stains. Given this information, translucency then becomes a predominant factor in predicting esthetic outcomes and the selection between restorative materials (Kelly, 1996). When these conditions are met and properly understood, esthetic restorations can result instead of an artificial appearance.

There are several factors which contribute to the resulting appearance of a restoration; chemical and physical composition of the material, thickness of the material, angle of incidence of light, and structures backing the material. Each of these qualities or conditions will affect the appearance of the restoration in different ways. The composition and the thickness of the material influence the ability of light to pass through the material. Typically, the greater the thickness, the less light is able to pass through, resulting in less translucency. The primary factor affecting translucency and appearance is typically the amount of glass contained in a material. Glass creates translucency because the crystalline structure is very irregular and allows light to pass through it. The higher the glass content, the higher the translucency. Materials that are opaque in composition will permit less light to pass through the restoration. Restorations made at minimal thickness are especially susceptible to this property. Lastly, the angle of incidence of light will affect the appearance because the lower the degree of incidence, the greater the amount of light is reflected.

The structures supporting the material will also affect the optical properties. The supporting material can be opaque or translucent, high in value or low in value, and these characteristics can have a tremendous effect on the resulting appearance. For opaque materials, the underlying material will largely be obscured, and less consideration is needed for the supporting structure. However, materials that are very translucent and will allow light to pass through the restoration and be reflected will need more consideration as to how much change can be anticipated. Because of this, translucent restorations are considered to have a poor masking ability.

The purpose of this study is to investigate the optical properties of a novel restorative material, a lithium aluminosilicate reinforced with lithium disilicate, under conditions that modify material thickness and supporting structure. The study also aims to compare the HT and LT versions of the material. The information gathered from observing the material under various conditions will benefit clinicians by increasing the predictability in using the material to create esthetic restorations for patients.

**Hypotheses**

There are two null hypotheses for this study.

1. The first null hypothesis of the study is that there is no difference in translucency between the HT and LT material.
2. The second hypothesis is that there is no significant change in color with composite, titanium, or zirconia supporting structures.

# CHAPTER II: LITERATURE REVIEW

## Light, Color, and Perception

Light is the energy that is interpreted by human photo-sensory organs to form our perception of sight. The way light is perceived is affected by the light source, time of day, environment, and viewing angle. It is also affected by the individual receiving the wavelengths of light and their individual neurosensory abilities. Metamerism is another important property to consider when discussing tooth color. Metamerism is when the same object appears to have different color because of different light sources (Watts and Addy 2001).

Because light energy has many wavelengths in the visible spectrum, systems have emerged to help qualify color. The two primary systems used in discussing color are the Munsell system and the CIE system (Commission Internationale de l'Eclairage) (Judd et al. 1933).

The Munsell system describes color in terms of Value, Hue, and Chroma. The most important variable regarding dental shade matching is value. This characteristic is defined with lower values indicating darker objects (Moser et al. 1978). The Hue of an object of an object in the Munsell color system is the distinctive coloring of the object, such as green or blue and the chroma is the intensity of the hue. The higher the chroma for a particular hue, the more prominent the hue in a particular object (Nickerson 1940).

The CIE color coordinate system is another common system in use to describe color. This system uses tristimulus colorimetry to define color coordinates in the visible spectrum (Judd et al. 1933). In the L*a*b* system, the L coordinate represents a measure of lightness, similar to value, and a* and b* values represent coordinate on a red/blue and yellow/green axis (Ghinea et al. 2010).

Human perception of color is a very subjective affair. Every individual will have different abilities, even in perfectly healthy individuals. Conditions such as eyesight, colorblindness, patient complexion, clothing, and ambient lighting can significantly change how an individual perceives an object. Even at the dental level, the finishing of the restoration will affect how light is affected and how it will appear to an observer. This leads to unpredictable differences and color matching between observers (Ishikawa-Nagai et al. 2009).

Several studies have looked at what change in color is detectable by human observers. Ruyter et al. (1987) performed a study to determine the 50% acceptability for change in color and found the average $\Delta E_{ab}$ value to be 3.3. Paravina et al. (2009) determined the perceptibility threshold to be $\Delta E_{ab}$ 1.2 and the acceptability threshold to be $\Delta E_{ab}$ to be 2.7 for dental ceramic restorations. In this same study, the $\Delta E_{00}$ acceptability threshold was found to be 1.8 and perceptibility to be 0.8 (Paravina et al. 2009).

**Optical Properties of Natural Teeth**

The appearance of natural teeth is influenced by the optical properties of enamel and dentin. The ratio of these two issues also plays a role in appearance as there is a color change from incisal to gingival third due to less enamel being present in the cervical third of a tooth and significantly more in the incisal or occlusal third (Watts and Addy 2001). These two different layers of tooth structure have difference functions, and therefore different compositions which affect their appearance and light properties. The reflectance of light by enamel and dentin, and the scattering of light by these tissues determine the appearance of the tooth (Chayabutr, 2011). It is the paths of light inside the teeth and their reflectance which determine tooth color and appearance (Joiner, 2004, Ten Bosch and Coops 1995). It also cannot be ignored that teeth discolor throughout a life time due to intrinsic factors such as secondary dentin formation and extrinsic staining (Watts and Addy 2001). Therefore, understanding the optical properties of these tissues is an important factor in replicating them with naturally appearing dental restorations.

The first layer of hard tissue that light encounters is the enamel. Properly developed enamel is composed of hydroxyapatite crystals and has only half a percent of organic matter. Under normal circumstances, enamel is translucent with a relative translucency parameter of 18.7 at 1-millimeter thickness. It has a negligible scattering effect except in the blue range (Yu and Lee, 2009). The hydration of this tissue also plays a significant role. Enamel is subject to dehydration which will affect translucency of the tissue. When enamel is dehydrated, the water in the enamel is replaced by air, and due to the difference in refractive indices, the translucency is affected (Brodbelt et al. 1981). The refractive index of enamel is 1.7, water is 1.33, and air is 1.0. Therefore, dehydrated enamel is less translucent (O'Brien 1985). Yu et al. (2009) determined the L* a* b* values for enamel are lower than dentin of the same thickness which indicates that enamel is darker and has a greater amount of red color than dentin. Because of these properties, enamel has less of an effect on overall appearance than dentin and does not require much consideration.

Dentin is the next layer encountered by light and is not as translucent. Unlike enamel, dentin has varying characteristics throughout the mouth. Overall, dentin has a greater organic composition which results in a lower relative translucency parameter of 16.4 at 1mm thickness. This value varies from anterior to posterior teeth, however, with anterior teeth having a TP of 6.85 and posterior teeth averaging 21.49. Generally, anterior teeth have a lower L* values, indicating lighter value, but are less translucent with a relative translucency parameter average of 6.85 as found by Pop-Ciutrila et al. (Pop-Ciutrila, 2016). This means that the dentin of anterior teeth will reflect more light back through the restoration than posterior teeth and the color of the dentin becomes an important consideration.

It is also dentin which primarily determines the color of teeth. Enamel plays very little role in the determination of color (Ten-Bosch and Coops, 1995). While enamel is typically more translucent than dentin, the dentin is greater in thickness and this is what plays a significant role in the appearance of teeth (Yu et al. 2009). Anterior teeth tend to be lighter and have higher L* values whereas posterior teeth tend to be darker and more polychromatic, giving lower L* values and higher a* and b* values (Pop-Ciutrila, 2016).

**Optical Properties of Dental Restorations**

The desired outcome of dental restorations is to properly mimic the optical properties exhibited by natural teeth. The ability to accomplish this will be affected by several variables. Translucency is an important variable which is determined primarily by the material and the thickness (Wang, 2013). In ceramic restorative materials, the thickness and translucency are usually directly related (Chu et al. 2007, Ozturk et al. 2008). The greater thickness of the material, the less light passes though it and results in a lower translucency (Yu and Lee 2009). However, the amount of change in translucency with change in thickness of material can vary between materials (Wang, 2013).

Another important characteristic is the supporting structure for a restoration (Azer et al. 2011). Ceramic restorations are susceptible to color change, especially if the dentin is discolored or if the restoration is supported by an implant (Chaiyabutr, 2011). This can be especially important if the restoration is supported by a dental implant. This creates a primary difference in the restoration from a traditional tooth borne restoration because dentin will affect light and appearance much differently than an implant abutment. The dentin of a natural tooth will affect the color and show through a translucent restoration, but will still allow some light to pass into the dentin and create a natural appearance, even when the dentin is dark or stained. Titanium or zirconia abutments will affect the light very differently, allowing very little light penetration into the abutment. With gray titanium, this can cause a significant darkening of the restoration because it reflects all the light that is not absorbed. This can also be seen with anodized titanium abutments. Zirconia abutments typically do not have this affect and can offer more predictable esthetic results.

Other factors which can affect the appearance of a ceramic restoration include the cement used, the number of firings, and surface gloss (O'Brien et al. 1984). Adhesive resin cement can be opaque, translucent, or have other tones associated with it. While an opaque cement may aid in blocking out discolored dentin or darker abutments, it does not have as much of an effect as thickness or material of the restoration (Chaiyabutr et al, 2011). However, it does tend to darken the restoration. Terzioglu et al. (2009) found that significant $\Delta E$ values for all restorations in the study after cementation with a resin cement, but did not find significant differences when comparing the shade of cement used. The number of firings of all ceramic restorations can also affect the final color result (Ozturk, 2008).

There are several primary restorative materials in use for esthetic restorations. While each material has characteristics that make it more appropriate for certain clinical situations, the primary aim is to discuss optical properties. Wang et al. determined the Translucency Parameter of several glass ceramic restorations, including IPS e.max Press and CAD, and found the TP to range from 14.9-19.6 at 1mm thickness (Wang et al., 2013). This approximates the TP of human enamel and dentin at 1mm, with TP values of 18.1 and 16.4 respectively (Pop-Ciutrila, 2016). However, Wang et al. also determined the TP range of zirconia and found it to range from 5.5-13.5, which places this slightly lower than the TP established for enamel and dentin. This agrees with other studies that found zirconia to be less translucent than glass ceramic restorations as different crystalline compositions result in different translucencies.

Another important ceramic restorative material is porcelain, which is either bonded to metal or can be employed as a veneer restoration or jacket crown. Chu et al. (2007) studied several types of porcelain at 0.7mm thickness to evaluate their translucency and also their masking ability. The contrast ratio ranged from 0.5 to 0.39 for the three porcelains and the $\Delta E$ values were similar for all three. The study emphasized the difficulty that may present when using translucent material such as these with discolored dentin due to the poor masking ability.

**Lithium Aluminosilicate reinforced with Lithium Disilicate**

The test material in this study is a lithium aluminosilicate reinforced with lithium disilicate (Straumann n!ce, Basel, Switzerland). This is a new restorative material that is designed for single tooth restorations in the anterior or posterior supported by natural teeth or by implants. This material is fully crystallized so that it can be milled, finished, polished, and inserted without the need for firing. It has a manufacturer reported flexural strength of 350MPa (+/-50 MPa), which is comparable to other glass ceramic restorative materials but still significantly less than zirconia and IPS e.max restorations (Kelly 1996, Vichi et al. 2016, Albero et al. 2015). The manufacturer recommended minimal thickness for veneer preparations is greater than or equal to 0.6mm and greater than or equal to 1.0mm for partial or full coverage crowns. It is manufactured in high translucency and low translucency versions and most common dental shades.

**Measurement of Translucency**

Two measurements important to optical properties of ceramic restorations are the Contrast Ratio and the Translucency Parameter (Johnston et al., 1995). While they are similar measurements, their definitions are different and are an important distinction. The Contrast Ratio (CR) is a measure of translucency that is defined as the ratio of reflectance (Y) of a given material measured with a black backing (Yb) to the measure of reflectance of the same material with a white backing (Yw) (Antonson et al., 2001). CR ranges in value from 0 to 1, with 1 being total opacity and 0 being total translucency.

In 2010, Liu et al. determined the Translucency Perception Threshold using Contrast Ratio to be about 0.07 for 50% of subjects. Dental ceramics were evaluated by faculty, residents, and students in a dental school. They noted that experience plays a major role in being able to discern changes in translucency.

The other measure used to assess translucency is the Translucency Parameter (TP). This is defined as the color difference ($\Delta E$) between a sample of uniform thickness measured with a white and black backing (Johnston et al., 1995). Yu et al. (2009) found TP to increase with larger aperture sizes for the photospectrometer readings. The perceptual threshold for humans with TP has yet to be defined.

**Instruments for Measuring Optical Properties**

Spectrophotometers can be used to measure translucency and color of dental restorative materials. Spectrophotometers are designed to measure ratios captured from measuring an object placed over a white background and then a black background. They also offer the advantage of being able to convert readings taken into other calculations of optical properties.

The edge loss effect occurs when light is transmitted through the edge of an object and not reflected back to the instrument (Yu et al. 2009). This can affect the accuracy of measurements by the instrument. To account for the edge loss effect, optical continuity can be maintained with an aqueous solution such as a sucrose solution, which eliminates air space between the specimen and the backing. This type of solution is also an index matching solution of approximately 1.5 which is similar to the backing.

## CHAPTER III: MATERIALS AND METHODS

Ingots of lithium aluminosilicate reinforced with lithium disilicate (Straumann n!ce, Basel, Switzerland) were obtained in high translucency (HT) and low translucency (LT) materials, both in shade A3. A precision, slow speed and water-cooled saw (Buehler Isomet 1000, Lake Bluff IL) was used to prepare samples measuring 10x10mm in area and 0.5mm, 1.0mm, 1.5mm, and 2.0mm in thickness. Each designated thickness of both HT and LT samples had five samples prepared with a tolerance of +/- 0.05mm which was verified with a digital caliper (World Precision Instruments, Sarasota FL). The samples were polished on one side using an appropriate glass ceramic chairside polishing kit (Meisinger, Neuss, Germany) following manufacturer recommendations and thickness was verified again with the same tolerance.

| Material | Number of Specimens fabricated | | | |
|---|---|---|---|---|
| | 0.5mm | 1.0mm | 1.5mm | 2.0mm |
| HT | 5 | 5 | 5 | 5 |
| LT | 5 | 5 | 5 | 5 |

**Table 1.** Number of specimens fabricated by thickness and translucency.

Samples were measured with a white and black background using a benchtop spectrophotometer with a 6mm aperture plate and illumination set to D65 at 2 degrees (X-rite CI 7600, Grand Rapids MI). The instrument was calibrated before each session and periodically throughout the measuring process. Prior to each reading, the samples were cleaned in an ultrasonic bath filled with distilled water for 1 minute and dried. A sucrose solution was used to maintain optical continuity and to reduce the edge loss effect. After each reading, each sample was again cleaned in the ultrasonic bath for 1 minute and dried.

For the readings where abutment backings were simulated, the same cleaning and reading protocol was followed. Three materials were used to simulate various clinical conditions. A packable composite in shade A3 at 3mm (Filtek Supreme Ultra, USA) was selected to replicate dentin as the supporting structure. Unpolished 10x10mm titanium squares were used to replicate an implant abutment made of non-anodized titanium. The final group was unpolished zirconia measuring 10x10mm and in shade A1. Between each specimen and backing, a neutral try in paste was used to maintain optical continuity (Variolink Esthetic, Ivoclar, Sarasota FL) and provide consistent readings.

All data was captured by the photospectrometer and computed using software (Color I Control, X Rite). Values for L, a, b, C, H, and Y were recorded. To calculate the color difference, the CIEDE2000 formula was followed as $\Delta E_{00}=(L_1^*,a_1^*,b_1^*;L_2^*,a_2^*,b_2^*)$ (Sharma et al., 2005).

## CHAPTER IV: RESULTS

The mean Contrast Ratios and Translucency Parameters were calculated for High Translucency and Low Translucency lithium aluminosilicate reinforced with lithium disilicate as a baseline. The L* a*and b* values were also calculated to determine ΔE with composite, titanium, and zirconia backings. The values for individual samples are given in Appendix X (Raw Data). The baseline contrast ratio for both HT and LT material was found to be exponentially related to material thickness where the thicker the material, the higher the contrast ratio. The HT material showed lower CR values at each thickness except at 0.5mm.

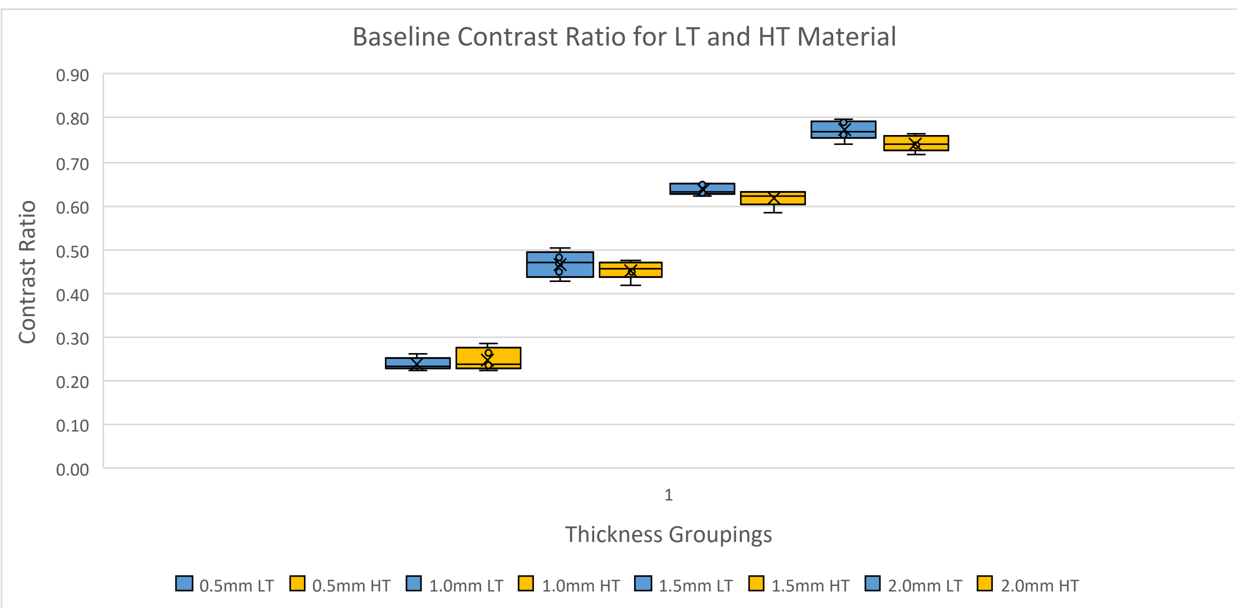


**Figure 1.** Baseline Contrast Ratio for LT and HT material with mean, median, and standard deviation.

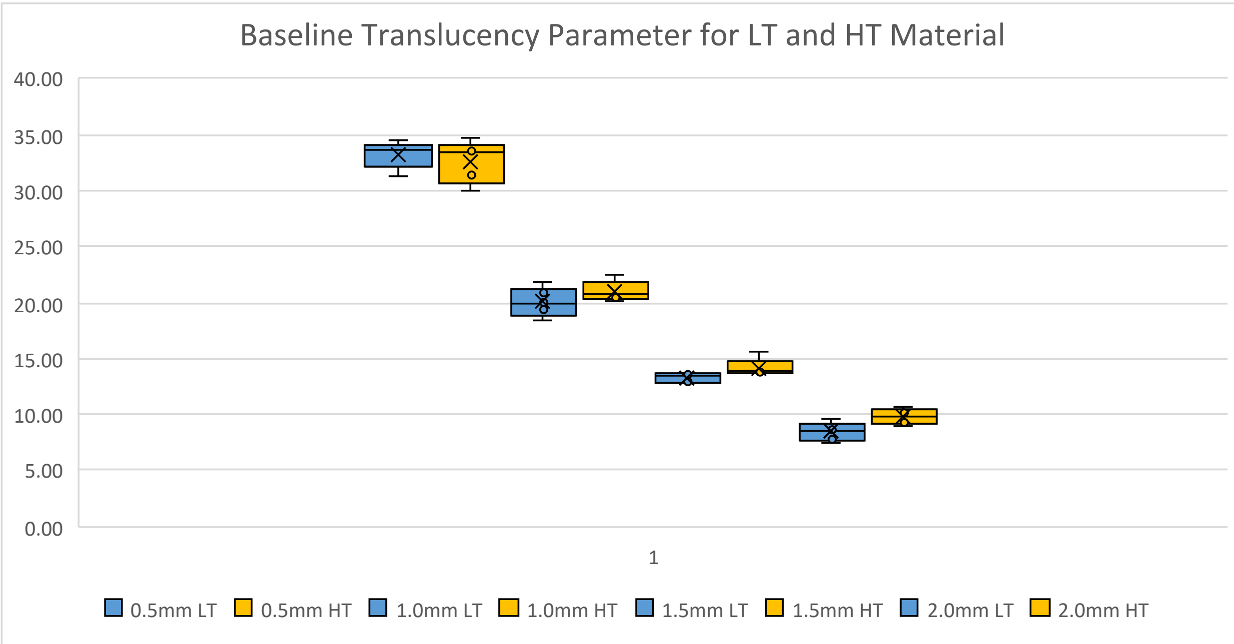


**Figure 2.** Baseline Translucency Parameter for LT and HT material with mean, median, and standard deviation.

The values recorded for Delta E are shown in the following figures. Zirconia backings showed the least amount of change as compared to the composite and titanium backings. It was also found that the thicker the specimen the less change in color was observed.

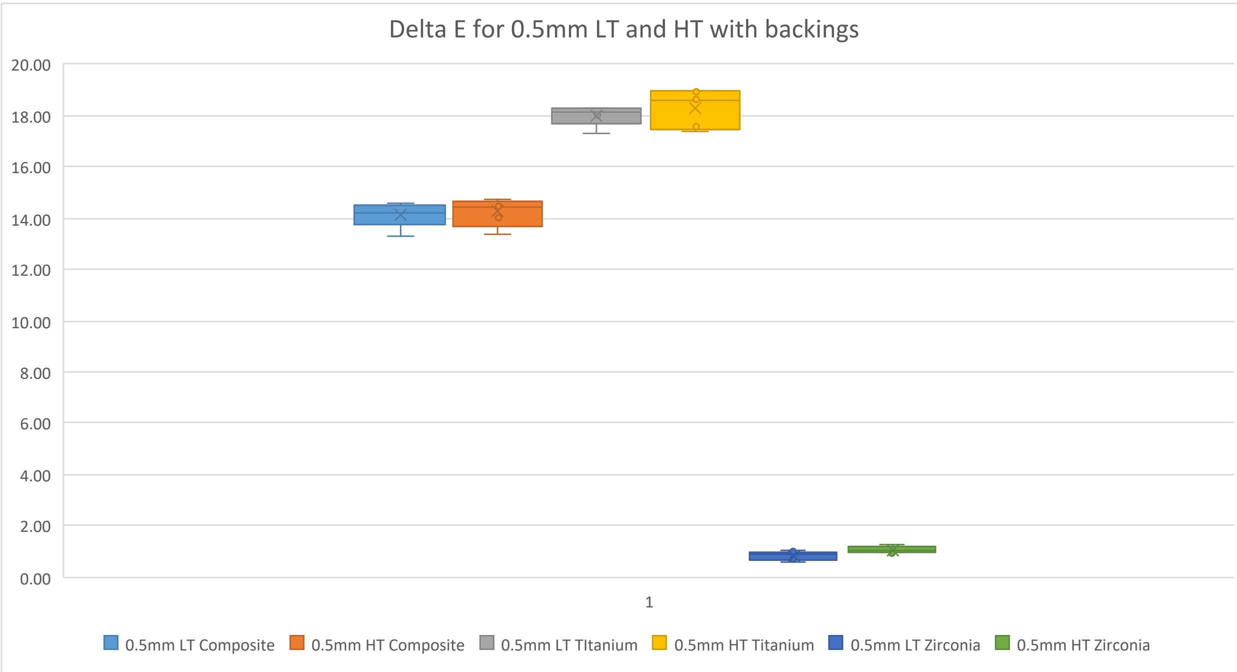


**Figure 3.** Delta E values for 0.5mm LT and HT material with mean, median, and standard deviation.

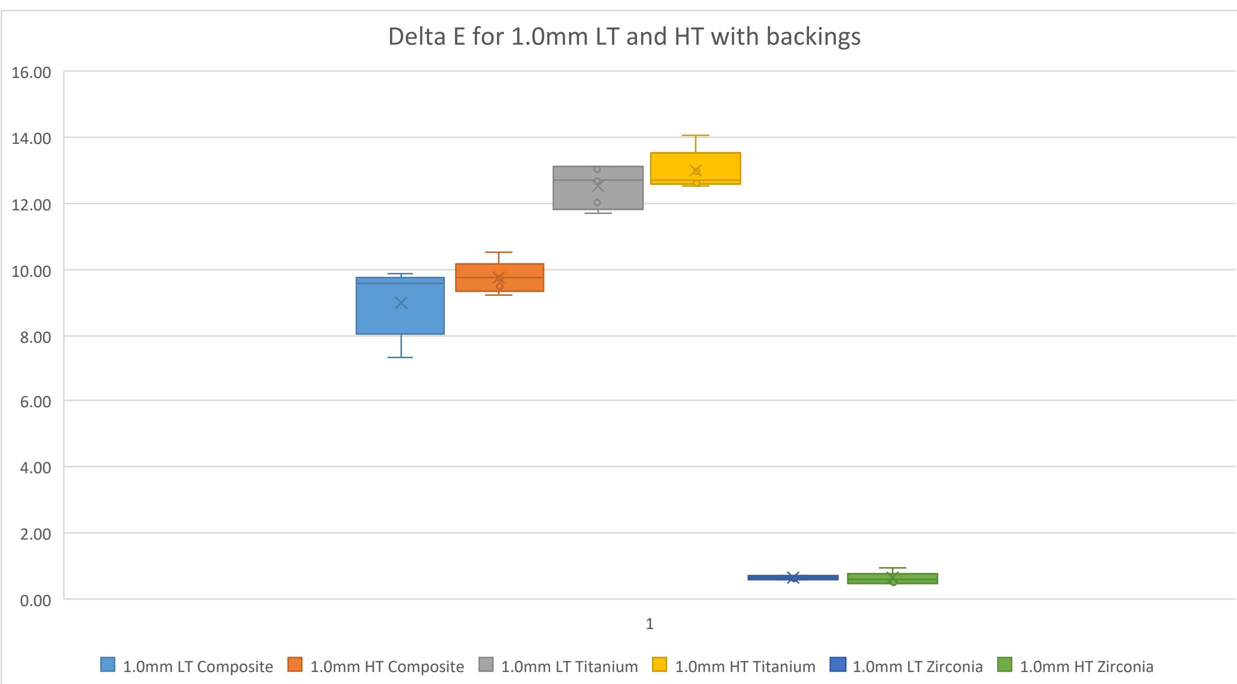


**Figure 4.** Delta E values for 1.0mm LT and HT material with mean, median, and standard deviation.

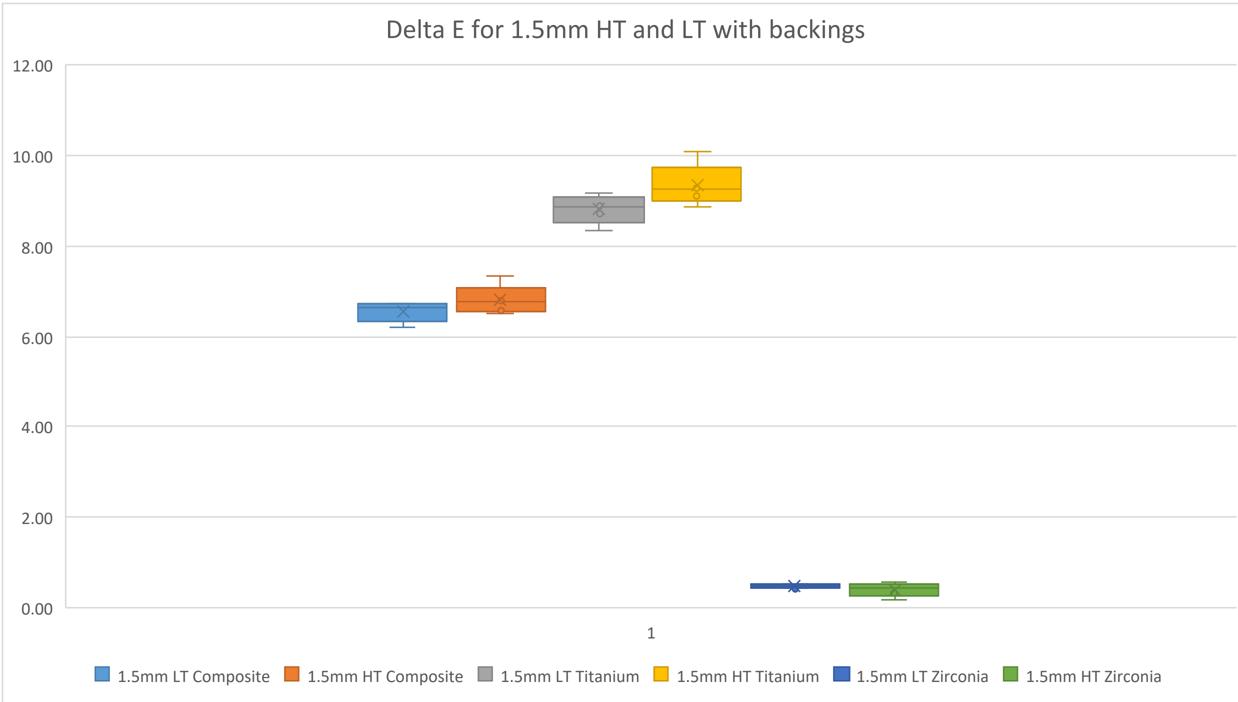


**Figure 5.** Delta E values for 1.5mm LT and HT material with mean, median, and standard deviation.

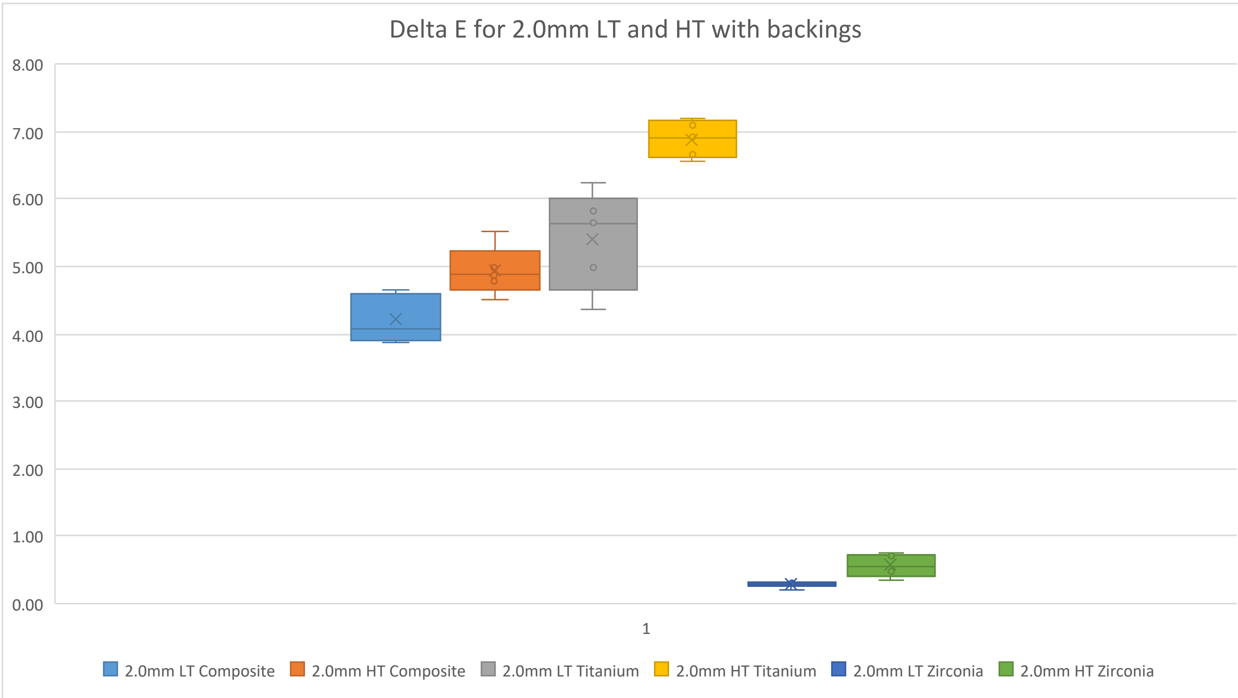


**Figure 6.** Delta E values for 2.0m LT and HT material with mean, median, and standard deviation.

**Statistical Analysis**

A statistical analysis was performed by university statisticians. The specific analyses and results are discussed subsequently.

For comparing the translucency of the HT and LT materials, a linear regression was performed using the baseline data to examine the TP 2000 data and the Contrast Ratio data. For both assessments, neither the TP 2000 ($p=0.3901$) nor the CR ($p=0.1379$) found a significant difference between the HT and LT materials for translucency.

Regarding the effects of material backing on the translucency of the subject material, separate models were generated by thickness of test material (0.5mm, 1.0mm, 1.5mm, 2.0mm). For each model, outcomes of CR and TP 2000 were fit against material backing and tests of significant interactions were made to compare differences in backing material within HT and LT test materials. The same test was also performed to compare differences of translucency between each backing material.

At 0.5mm, significant differences were found within each level of translucency between the backing materials Composite, Titanium, Zirconia with TP 2000 outcomes. Using LT material, differences between the different backings were observed with the following tests: Composite vs. Titanium ($p<0.0001$), Titanium vs. Zirconia ($p<0.0001$), and Composite vs. Zirconia ($p<0.0001$). Using HT material at 0.5mm thickness, significant differences between Composite vs. Titanium ($p<0.0001$), Titanium vs. Zirconia ($p<0.0001$), and Composite vs. Zirconia ($p<0.0001$) were observed. For each material backing at thickness of 0.5mm, HT vs. LT materials with composite backing were significantly different using a Least Squares Means test (0.6074). HT vs LT material with Titanium backing for 0.5mm was not significantly different using a Least Squares Means Test (0.0982). HT vs LT material with Zirconia backings was significantly different at 0.5mm (0.0222).

At 1mm thickness, no differences in the HT vs LT material were detected in a test for interaction terms so they were removed from the model ($p=0.9550$). However, differences between the material backings were detected for TP 2000 outcomes. Tests of Composite vs Titanium, Composite vs Zirconia, and Titanium vs. Zirconia all had significant values ($p<0.0001$).

At 1.5mm thickness, no differences in the HT and LT material were detected so they were removed from the model ($p=0.5112$). The TP 2000 outcomes between Composite, Titanium, and Zirconia were significant ($p<0.0001$).

At 2mm thickness with outcome of TP 2000, joint test of interaction was significant so (p=0.0361) so all variables were kept in the model. Within each level of translucency there is a difference in the 3 materials (p=0.0083, p<0.0001).

When using CR as the outcome, the joint test of interaction was not significant at any thickness so all models were fit for main effects only.

## CHAPTER V: DISCUSSION

The individual specimen data for Contrast Ratio, Translucency Parameter, and Delta E values are listed in Appendix A Raw Data.

### Thickness and Translucency

The dental literature already supports that translucency is inversely related to thickness Sulaiman et al., 2015, Antonson et al. 2001, Wang et al. 2013). This study examined both Contrast Ratio and Translucency Parameter as it relates to thickness of the subject material. Both the Contrast Ratio and the Translucency Parameter values agree with other published studies in showing that as the restoration thickness increases, less translucency is observed with the material (Sulaiman et al., 2015). Also, in agreement with other studies, TP and CR are inversely correlated.

The material itself is very translucent. The Contrast Ratio and Translucency Parameter readings indicate that both the HT and LT materials allow a significant amount of light to pass through. At 1mm thickness the CR of HT and LT materials were 0.45 and 0.47, respectively. Compared to other common translucent restorative materials, the CR of IPS Empress CAD at 1mm is 0.59 and the CR of IPS e.max CAD at 1mm thickness is 0.64 (Sulaiman et al., 2015).

As with other translucent restorations, a stump shade will be very important. This is to aid the clinician in translating the clinical shade desired and the shade of the supporting structure, into the desired final result. A conversion chart may be necessary to aid the laboratory technician or provider to take a clinical shade and correlate it with the manufacturer’s listed shade values.

## High Translucency and Low Translucency Material

One objective of the study was to examine if there was a difference between the HT and LT materials. The results from the TP 2000 and Contrast Ratio regressions show that there is no clinically significant difference between the HT and LT materials. There was statistical difference noted at 0.5mm thickness between HT and LT with supporting materials in place. This was the only thickness where a difference between the HT and LT materials was noted. At all readings, however. the values obtained are within 0.06 units of each other. From a clinical perspective, because the readings are within this perceptibility range of each other, they are not visually distinct at baseline. A casual observer would not be able to differentiate between the two materials either by themselves or in clinical application.

## The Effect of Supporting Structures

The Delta E values obtained from this study show a significant color change for composite and titanium backings. All readings for these two supporting structures are over the published 1.8 acceptability threshold as published by Paravina et al. (2015). The only backing that was within the acceptable limits for change in color at all readings was the zirconia supporting structure.

The significant color change observed indicates a poor masking ability for the ceramic restoration. This is a common problem with ceramic restorations, especially as they become more translucent. Because this material is very translucent, this is what is expected. This can pose certain challenges clinically for providers because masking dark or discolored teeth will be very difficult. Any metal, such as a cast post and core, or a titanium implant abutment, will almost certainly show through the translucent ceramic. The only supporting structure that did not cause a significant change was the zirconia backing. This supporting structure would be highly recommended for any implant restorations, especially in the esthetic zone.

Because of the poor masking ability, clinicians should be cautious with its application in the esthetic zone and choose cases wisely. Younger unrestored teeth with a high degree of translucency will be good indications for this material. Older teeth that are darker, discolored, or heavily restored may require a less translucent material to achieve the desired outcome. For implant restorations, a zirconia coping will be required to prevent a shadowing effect from the titanium abutment even with thick restorations.

**Study Limitations**

The individual instruments and equipment used for the study can create differences in values obtained between laboratories. The amount of time spent finishing, and the technique of the individual operator conducting the study can also affect results obtained. This was managed by limiting the number of operators producing and reading specimens to two.

The number of samples prepared, while low, is typically sufficient for this type of optical study. However, with more samples prepared, more accuracy may be obtained for the parameters studied and stronger statistical analysis would be available. While the instrument was calibrated before each session and as needed during the data acquisition, slight discrepancies may result from repeated openings of the gate or how the specimen were held for readings. This was managed by limiting the number of operators performing the readings.

**Suggestions for Future Research**

Future research could involve direct comparisons to other commonly used restorative materials. A direct comparison between zirconia and other ceramic restorations, such as IPS e.max, would be helpful to clinicians. Including a gold hue implant abutment would be another valuable inclusion in a future study.

Instead of using try in paste, evaluating the effect of cement would be important for evaluating masking abilities. The effects of various types of resin cement would be very beneficial to clinicians. Opaquer could also be used in this study to see how much difference in masking ability is obtained.

## APPENDIX A: RAW DATA

| 0.5mm LT | TP 2000 | CR |
|---|---|---|
| 1 | 31.29 | 0.26 |
| 2 | 33.72 | 0.23 |
| 3 | 34.41 | 0.22 |
| 4 | 33.00 | 0.24 |
| 5 | 33.70 | 0.23 |
| Mean | 33.72 | 0.24 |
| SD | 1.19 | 0.02 |

**Table 2.** Raw data for 0.5mm LT material baseline.

| 1.0mm LT | TP 2000 | CR |
|---|---|---|
| 1 | 18.49 | 0.50 |
| 2 | 19.29 | 0.48 |
| 3 | 20.82 | 0.45 |
| 4 | 19.97 | 0.47 |
| 5 | 21.76 | 0.43 |
| Mean | 20.07 | 0.47 |
| SD | 1.28 | 0.03 |

**Table 3.** Raw data for 1.0mm LT material baseline.

| 1.5mm LT | TP 2000 | CR |
|---|---|---|
| 1 | 13.74 | 0.62 |
| 2 | 12.84 | 0.65 |
| 3 | 13.53 | 0.63 |
| 4 | 12.87 | 0.65 |
| 5 | 13.37 | 0.63 |
| Mean | 13.27 | 0.64 |
| SD | 0.40 | 0.01 |

**Table 4**. Raw data for 1.5mm LT material baseline.

| 2.0mm LT | TP 2000 | CR |
|---|---|---|
| 1 | 8.63 | 0.77 |
| 2 | 8.86 | 0.76 |
| 3 | 7.88 | 0.79 |
| 4 | 9.60 | 0.74 |
| 5 | 7.51 | 0.80 |
| Mean | 8.50 | 0.77 |
| SD | 0.82 | 0.02 |

**Table 5.** Raw data for 2.0mm LT material baseline.

| 0.5mm HT | TP 2000 | CR |
|---|---|---|
| 1 | 29.98 | 0.29 |
| 2 | 34.73 | 0.22 |
| 3 | 33.45 | 0.24 |
| 4 | 31.31 | 0.27 |
| 5 | 33.43 | 0.24 |
| Mean | 32.58 | 0.25 |
| SD | 1.90 | 0.03 |

**Table 6.** Raw data for 0.5mm HT material baseline.

| 1.0mm HT | TP 2000 | CR |
|---|---|---|
| 1 | 20.44 | 0.46 |
| 2 | 20.13 | 0.47 |
| 3 | 22.42 | 0.42 |
| 4 | 20.81 | 0.46 |
| 5 | 21.03 | 0.45 |
| Mean | 20.97 | 0.45 |
| SD | 0.88 | 0.02 |

**Table 7.** Raw data for 1.0mm HT material baseline.

| 1.5mm HT | TP 2000 | CR |
| --- | --- | --- |
| 1 | 13.76 | 0.63 |
| 2 | 14.01 | 0.62 |
| 3 | 13.96 | 0.62 |
| 4 | 15.57 | 0.58 |
| 5 | 13.60 | 0.63 |
| Mean | 14.18 | 0.62 |
| SD | 0.79 | 0.02 |

**Table 8.** Raw data for 1.5mm HT material baseline.

| 2.0mm HT | TP 2000 | CR |
| --- | --- | --- |
| 1 | 9.73 | 0.74 |
| 2 | 10.13 | 0.74 |
| 3 | 8.93 | 0.76 |
| 4 | 9.37 | 0.75 |
| 5 | 10.66 | 0.72 |
| Mean | 9.76 | 0.74 |
| SD | 0.67 | 0.02 |

**Table 9.** Raw data for 2.0mm HT material baseline.

| 0.5mm LT<br><br>Composite | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 2.51 | 0.96 | 13.28 |
| 2 | 2.57 | 0.96 | 14.22 |
| 3 | 2.79 | 0.95 | 14.60 |
| 4 | 2.71 | 0.95 | 14.17 |
| 5 | 2.75 | 0.95 | 14.46 |
| Mean | 2.67 | 0.95 | 14.15 |
| SD | 0.12 | 0.00 | 0.51 |

**Table 10.** Raw data for 0.5mm LT with composite.

| 1.0mm LT<br><br>Composite | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 1.67 | 0.97 | 8.67 |
| 2 | 2.11 | 0.94 | 7.34 |
| 3 | 1.82 | 0.97 | 9.88 |
| 4 | 1.69 | 0.97 | 9.55 |
| 5 | 1.90 | 0.96 | 9.57 |
| Mean | 1.84 | 0.96 | 9.00 |
| SD | 0.18 | 0.02 | 1.03 |

**Table 11.** Raw data for 1.0mm LT material with composite.

| 1.5mm LT Composite | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 1.37 | 0.98 | 6.73 |
| 2 | 1.35 | 0.99 | 6.19 |
| 3 | 1.33 | 0.98 | 6.65 |
| 4 | 1.23 | 0.98 | 6.45 |
| 5 | 1.30 | 0.99 | 6.68 |
| Mean | 1.32 | 0.98 | 6.54 |
| SD | 0.05 | 0.00 | 0.22 |

**Table 12.** Raw data for 1.5mm LT material with composite.

| 2.0mm LT Composite | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 0.94 | 0.98 | 4.08 |
| 2 | 0.86 | 0.99 | 4.55 |
| 3 | 0.82 | 0.99 | 3.86 |
| 4 | 0.75 | 0.99 | 4.65 |
| 5 | 0.78 | 0.99 | 3.96 |
| Mean | 0.83 | 0.99 | 4.22 |
| SD | 0.07 | 0.01 | 0.36 |

**Table 13.** Raw data for 2.0mm LT material with composite.

| 0.5mm HT Composite | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 2.45 | 0.96 | 13.37 |
| 2 | 2.38 | 0.96 | 14.75 |
| 3 | 2.73 | 0.96 | 14.46 |
| 4 | 2.66 | 0.97 | 14.00 |
| 5 | 2.88 | 0.95 | 14.61 |
| Mean | 2.62 | 0.96 | 14.24 |
| SD | 0.20 | 0.01 | 0.56 |

**Table 14.** Raw data for 0.5mm HT material with composite.

| 1.0mm HT Composite | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 1.91 | 0.97 | 9.23 |
| 2 | 1.71 | 0.97 | 9.48 |
| 3 | 1.91 | 0.97 | 10.53 |
| 4 | 1.93 | 0.97 | 9.72 |
| 5 | 1.87 | 0.97 | 9.76 |
| Mean | 1.87 | 0.97 | 9.74 |
| SD | 0.09 | 0.00 | 0.49 |

**Table 15.** Raw data for 1.0mm HT material with composite.

| 1.5mm HT Composite | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 1.39 | 0.98 | 6.52 |
| 2 | 1.35 | 0.98 | 6.84 |
| 3 | 1.34 | 0.98 | 6.78 |
| 4 | 1.48 | 0.98 | 7.32 |
| 5 | 1.26 | 0.98 | 6.56 |
| Mean | 1.36 | 0.98 | 6.80 |
| SD | 0.08 | 0.00 | 0.32 |

**Table 16.** Raw data for 1.5mm HT material with composite.

| 2.0mm HT Composite | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 0.96 | 0.99 | 4.97 |
| 2 | 1.05 | 0.98 | 4.88 |
| 3 | 0.57 | 1.00 | 4.52 |
| 4 | 0.89 | 0.99 | 4.78 |
| 5 | 0.93 | 0.97 | 5.51 |
| Mean | 0.88 | 0.99 | 4.93 |
| SD | 0.18 | 0.01 | 0.36 |

**Table 17.** Raw data for 2.0mm HT material with composite.

| 0.5mm LT Titanium | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 0.05 | 1.00 | 17.30 |
| 2 | 0.11 | 1.01 | 18.05 |
| 3 | 0.10 | 1.00 | 18.32 |
| 4 | 0.04 | 1.00 | 18.12 |
| 5 | 0.28 | 0.99 | 18.19 |
| Mean | 0.12 | 1.00 | 18.00 |
| SD | 0.10 | 0.01 | 0.40 |

**Table 18.** Raw data for 0.5mm LT material with titanium.

| 1.0mm LT Titanium | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 0.30 | 0.99 | 11.67 |
| 2 | 0.15 | 1.00 | 12.02 |
| 3 | 0.16 | 1.01 | 13.04 |
| 4 | 0.51 | 1.02 | 12.70 |
| 5 | 0.09 | 1.00 | 13.14 |
| Mean | 0.24 | 1.00 | 12.51 |
| SD | 0.17 | 0.01 | 0.64 |

**Table 19.** Raw data for 1.0mm LT material with titanium.

| 1.5mm LT Titanium | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 0.05 | 1.00 | 9.15 |
| 2 | 0.21 | 0.99 | 8.33 |
| 3 | 0.08 | 1.00 | 9.01 |
| 4 | 0.16 | 0.99 | 8.70 |
| 5 | 0.14 | 0.99 | 8.88 |
| Mean | 0.13 | 1.00 | 8.81 |
| SD | 0.06 | 0.01 | 0.32 |

**Table 20.** Raw data for 1.5mm LT material with titanium.

| 2.0mm LT Titanium | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 0.63 | 1.02 | 4.36 |
| 2 | 0.41 | 1.01 | 5.64 |
| 3 | 0.78 | 1.03 | 5.81 |
| 4 | 0.21 | 0.99 | 6.23 |
| 5 | 0.32 | 0.99 | 4.97 |
| Mean | 0.47 | 1.01 | 5.40 |
| SD | 0.23 | 0.02 | 0.74 |

**Table 21.** Raw data for 2.0mm LT material with titanium.

| 0.5mm HT Titanium | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 0.31 | 1.01 | 17.57 |
| 2 | 0.23 | 1.01 | 18.89 |
| 3 | 0.12 | 1.00 | 18.61 |
| 4 | 0.45 | 0.98 | 17.40 |
| 5 | 0.23 | 1.01 | 18.98 |
| Mean | 0.27 | 1.00 | 18.29 |
| SD | 0.12 | 0.01 | 0.75 |

**Table 22.** Raw data for 0.5mm HT material with titanium.

| 1.0mm HT Titanium | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 0.24 | 0.99 | 12.54 |
| 2 | 0.50 | 0.98 | 12.59 |
| 3 | 0.09 | 1.00 | 14.09 |
| 4 | 0.09 | 1.00 | 12.72 |
| 5 | 0.33 | 1.01 | 12.96 |
| Mean | 0.25 | 1.00 | 12.98 |
| SD | 0.17 | 0.01 | 0.64 |

**Table 23.** Raw data for 1.0mm HT material with titanium.

| 1.5mm HT Titanium | TP 2000 | CR | Delta E |
| --- | --- | --- | --- |
| 1 | 0.04 | 1.00 | 9.26 |
| 2 | 0.31 | 0.99 | 9.12 |
| 3 | 0.16 | 0.99 | 9.39 |
| 4 | 0.05 | 1.00 | 10.07 |
| 5 | 0.28 | 0.99 | 8.88 |
| Mean | 0.17 | 0.99 | 9.34 |
| SD | 0.13 | 0.01 | 0.45 |

**Table 24.** Raw data for 1.5mm HT material with titanium.

| 2.0mm HT Titanium | TP 2000 | CR | Delta E |
| --- | --- | --- | --- |
| 1 | 0.05 | 1.00 | 7.21 |
| 2 | 0.08 | 1.00 | 6.92 |
| 3 | 0.12 | 1.00 | 6.65 |
| 4 | 0.14 | 1.00 | 6.57 |
| 5 | 0.74 | 1.03 | 7.11 |
| Mean | 0.23 | 1.00 | 6.89 |
| SD | 0.29 | 0.02 | 0.28 |

**Table 25.** Raw data for 2.0mm HT material with titanium.

| 0.5mm LT Zirconia | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 1.70 | 0.94 | 0.56 |
| 2 | 1.77 | 0.94 | 0.91 |
| 3 | 1.77 | 0.94 | 0.97 |
| 4 | 1.72 | 0.94 | 0.72 |
| 5 | 1.61 | 0.94 | 1.01 |
| Mean | 1.71 | 0.94 | 0.83 |
| SD | 0.07 | 0.00 | 0.19 |

**Table 26.** Raw Data for 0.05mm LT material with zirconia.

| 1.0mm LT Zirconia | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 1.47 | 0.95 | 0.58 |
| 2 | 1.91 | 0.94 | 0.56 |
| 3 | 1.28 | 0.96 | 0.63 |
| 4 | 1.35 | 0.96 | 0.65 |
| 5 | 1.43 | 0.95 | 0.70 |
| Mean | 1.49 | 0.95 | 0.62 |
| SD | 0.25 | 0.01 | 0.06 |

**Table 27.** Raw Data for 1.0mm LT material with zirconia.

| 1.5mm LT Zirconia | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 1.39 | 0.96 | 0.47 |
| 2 | 0.99 | 0.97 | 0.41 |
| 3 | 0.83 | 0.98 | 0.52 |
| 4 | 1.12 | 0.97 | 0.41 |
| 5 | 1.19 | 0.95 | 0.51 |
| Mean | 1.10 | 0.97 | 0.46 |
| SD | 0.21 | 0.01 | 0.05 |

**Table 28.** Raw Data for 1.5mm LT material with zirconia.

| 2.0mm LT Zirconia | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 0.81 | 0.98 | 0.20 |
| 2 | 0.86 | 0.98 | 0.29 |
| 3 | 0.73 | 0.98 | 0.31 |
| 4 | 1.16 | 0.97 | 0.32 |
| 5 | 0.73 | 0.98 | 0.29 |
| Mean | 0.86 | 0.98 | 0.28 |
| SD | 0.18 | 0.01 | 0.05 |

**Table 29.** Raw data for 2.0mm LT material with zirconia.

| 0.5mm HT Zirconia | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 1.40 | 0.96 | 1.07 |
| 2 | 1.73 | 0.94 | 0.96 |
| 3 | 1.61 | 0.94 | 0.94 |
| 4 | 1.27 | 0.96 | 1.25 |
| 5 | 1.48 | 0.95 | 1.14 |
| Mean | 1.50 | 0.95 | 1.07 |
| SD | 0.18 | 0.01 | 0.13 |

**Table 30.** Raw data for 0.5mm HT material with zirconia.

| 1.0mm HT Zirconia | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 1.52 | 0.95 | 0.58 |
| 2 | 1.45 | 0.95 | 0.60 |
| 3 | 1.18 | 0.96 | 0.94 |
| 4 | 1.60 | 0.95 | 0.51 |
| 5 | 1.59 | 0.94 | 0.44 |
| Mean | 1.47 | 0.95 | 0.61 |
| SD | 0.17 | 0.01 | 0.19 |

**Table 31.** Raw data for 1.0mm HT material with zirconia.

| 1.5mm HT Zirconia | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 1.67 | 0.95 | 0.43 |
| 2 | 1.25 | 0.96 | 0.16 |
| 3 | 1.41 | 0.96 | 0.42 |
| 4 | 1.10 | 0.96 | 0.57 |
| 5 | 1.01 | 0.97 | 0.30 |
| Mean | 1.29 | 0.96 | 0.38 |
| SD | 0.26 | 0.01 | 0.15 |

**Table 32.** Raw data for 1.5mm HT material with zirconia.

| 2.0mm HT Zirconia | TP 2000 | CR | Delta E |
|---|---|---|---|
| 1 | 1.23 | 0.97 | 0.35 |
| 2 | 1.32 | 0.96 | 0.75 |
| 3 | 1.07 | 0.97 | 0.53 |
| 4 | 1.02 | 0.98 | 0.46 |
| 5 | 0.88 | 0.98 | 0.71 |
| Mean | 1.10 | 0.97 | 0.56 |
| SD | 0.17 | 0.01 | 0.17 |

**Table 33.** Raw data for 2.0mm HT material with zirconia.

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